EXPERIMENTAL AND MODELING STUDIES IN
FIXED-BED COAL GASIFICATION

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ABSTRACT

A laboratory scale fixed-bed coal gasification reactor was built with the objective of obtaining detailed temperature profiles inside the bed during the gasification process. Such data are needed in validating proposed models for fixed-bed gasification and in the estimation of suitable parameters for use with proposed models. This article describes the experimental setup and presents the results of a run using Wyoming coal. The experimental data are compared with simulation results obtained using a detailed two-dimensional model of the gasifier.

1. INTRODUCTION

Fixed-bed coal gasification is a commercially used technology for reacting coal with steam and oxygen to produce useful gases such as CH_4, CO, and H_2. Considerable work has been done lately on modeling of the fixed-bed gasifier. A rather detailed model was presented by Yoon et al. (1). Further improvements on this model have been made by Cho and Joseph (2) and Kim and Joseph (3). It has been difficult to establish the validity of these models fully because of the lack of sufficient operational data on commercial scale gasifiers. The research presented here was undertaken to remedy this situation by developing an experimental procedure for generating data which can be used directly in the verification of proposed models and to determine parameters that are required in the model. The paper contains a detailed description of the apparatus used, the experimental procedure and selected results on gasification of Wyoming coal. The paper also includes a brief sketch of the modeling effort and a comparison between the experimental data and model predictions.

2. DESCRIPTION OF EXPERIMENTAL SETUP

In a commercial scale fixed-bed gasifier, coal is fed continuously at the top at a slow rate while steam and oxygen (or air) is fed at the bottom. The coal undergoes drying and devolatilization at the top of the gasifier and char descends slowly through the reactor. Because the char-bed is moving slowly it is termed as a fixed-bed reactor. For the purposes of this research it was decided that the runs will be conducted on a bed of char which is stationary. Hence it approximates the commercial process with the coal feed cut off. The resulting transient data (since we will have a reaction front moving through the char bed) is then used for validating models of gasifiers.

Figure 1 shows the schematic of the experimental setup. The major pieces of equipment are a steam generator, feed preheater, the tubular reactor, a condenser for removing tars and water, gas chromatograph for product gas analysis and a data acquisition system for monitoring the temperature.

The gasification vessel is a 4 in. diameter, 4 ft. long cylindrical stainless steel tube insulated with refractory and surrounded by a 6 inch diameter stainless steel tube. The vessel can be operated at temperatures as high as 1200°C. This reactor is packed with devolatilized coal. The devolatilization is carried out separately in another furnace in a nitrogen atmosphere at a temperature of approximately 800°C until no further weight loss occurs. The coal used is in the size range 8 - 20 mesh (2.3 - .833 mm). Each run requires approximately 4 kg of coal. A superficial gas velocity of approximately 1 ft/sec is used in the gasifier.

Figure 2 shows a detail of the gasification reactor. The reactor is designed to operate close to atmospheric pressure. Heat losses are minimized by a refractory lining around the reactor tube and by ceramic beads at both ends of the tube. An ignition coil at the top of the bed is used to start the combustion reaction. Initially the inside liner of the gasifier was constructed with ceramic but it cracked repeatedly due to thermal shock.

The product gases are sent through a condenser and liquid separator to remove water, tar and ash. The remaining gases are flared. A sample is sent through the GC for analysis every 15 minutes.

Temperature profiles in the bed are measured by means of two thermowells inserted axially at $r = 0$ and $r = .36$ cm. Type K (chromel/alumel) thermocouples were used. The thermocouple locations are shown in Figure 2. The data from the thermocouples was collected by means of an LSI/11 microcomputer and stored on tape. This data was then transmitted to a DEC-20 mainframe where the data is analyzed further.

3. EXPERIMENTAL RESULTS

Two successful runs were made using char generated from Wyoming coal. The results of the second run are reported here. The coal analysis is given in Table 1. The operating conditions of the gasifier are reported in Table 2. Note that the air flow had to be decreased after 45 minutes to maintain the maximum temperatures below 1200°C. The run was terminated after 50 minutes. An analysis of the material remaining in the gasifier indicated some unconverted carbon (see Table 2). The bed length was only 12 cm indicating that the ash collapsed.

The results of the run are shown in Figures 3, 4 and 5. Figure 3 shows the temperature profiles of the inner thermocouples. Note that after the temperature has reached a peak, the thermocouple is sitting in a bed of ash and the drop in termperature is caused by heat loss from the bed to the walls and the gases. The peak temperatures are around 1200°C and the peak value decreases as the bed is reacted. Also there is a considerable spreading of the profile in the axial direction towards the end of the run.

Figure 4 shows the temperature profiles of the outer thermocouples. These temperatures are notably lower than the inner ones. This is not surprising since the wall acts as a heat sink lowering the temperatures close to the wall. Also the spreading of the temperatures in the axial direction is seen in this set of profiles also.

Figure 5 shows the product gas composition as a function of time. After the initial transient the composition attains nearly constant values. There is some oxygen bypassing in the gasifier. The fluctuations are probably caused by errors in analysis. Due to the use of helium as the carrier gas in the gas chromatograph, hydrogen analysis had a large correction factor and hence has greater error than the other gases. Attempts on closing a hydrogen mass balance around the system confirmed this.

Whether or not the oxygen bypassing occured through the bed or the insulated wall is difficult to determine. As the reaction progresses, the bed length decreases and hence the associated pressure drop through the bed also decreases. This might have contributed to decreased bypassing of the oxygen.

4. COMPARISON WITH SIMULATION RESULTS

In parallel with this experimental investigation, a modeling study was conducted with two objectives. The first was to be able to study the behavior of large scale fixed-bed gasifiers such as the Lurgi-type. The second was to be able to validate the model using the results from the laboratory scale gasifier. The details of the model was published elsewhere (Joseph, et al., 1983). A brief summary is given here.

In a typical commercial scale gasifier the coal is moving at a much smaller velocity than the gases. As a result, the gasifier can be divided into two zones, one for drying and devolatilization and another for combustion and gasification. The first zone is relatively narrow and can be assumed to take place instantaneously for practical purposes. It is the second zone that determines the operating characteristics of the gasifier. In this zone, char descends slowly reaching with the gases rising from the combustion zone. This was the reason for using char instead of coal in the experimental studies. The main reactions in this zone are char-oxygen, char-steam, char-carbon dioxide and the water-gas shift reaction. In addition to these reaction kinetics, the heat and mass transfer in both axial and radial directions play a significant role.

A number of assumptions are required to develop a model that is both mathematically and computationally tractable. Some major assumptions include a shrinking-core model for gas-solid kinetics, no axial dispersion of heat and a homogeneous gas-solid temperature in the bed. The equations resulting from the mass and energy balances are solved numerically using suitable integration methods. The interested reader is referred to Joseph et al. (4).

Figures 6 and 7 show a comparison of temperatures predicted by the model and those experimentally observed. The agreement between the two during the early part of the run is good. However the temperature profiles predicted by the model tend to be rather uniform with respect to time whereas the experimental profiles exhibit a marked decrease in the peak value and a spreading of the profile in the axial direction.

Similar trends were observed in another run as reported in Salam (5). This spreading of the temperature profile could have been caused by a number of reasons. Sources of modeling errors include (i) axial dispersion of heat (ii) thermal storage and conductivity of the thermowells (iii) reduction in bed length caused by collapsing ash layer (iv) effect of heat transfer by radiation to the walls and (v) effect of channeling and bypassing of oxygen through the bed.

5. CONCLUSIONS

This paper presented the results of a char gasification run using Wyoming coal in a fixed-bed laboratory gasifier. The temperature profiles in the bed at various axial and radial positions are presented as a function of time. The results are useful in validating proposed models for fixed-bed gasifiers. Comparison with one such model indicates that the model is capable of predicting the initial temperature profiles reasonably well, but requires further refinement to be able to explain some flattening trends in the temperatures. Current research is focused on trying to update the model in order to explain the experimental observations.

6. REFERENCES

1. Yoon, H., J. Wei and M. M. Denn, "Model for Moving-Bed Coal Gasification Reactors", AIChE Journal 24, p. 885 (1978).

2. Cho, Y. S. and B. Joseph, "A Heterogeneous Model for Moving-Bed Coal Gasifiers", Industrial and Engineering Chemistry, Process Design and Development, Vol. 20, 318 (1981).

3. Kim, M. and B. Joseph, "Dynamic Modeling of Moving-Bed Coal Gasifiers", Industrial and Engineering Chemistry, Process Design and Development, Vol. 22, 212 (1983).

4. Joseph, B. A. Bhattacharya, L. Salam and M. P. Duduković, "Modeling and Simulation of Fixed-bed Coal Gasification Reactors, Systems Simulation of Fossil Energy Processes", Symposium organized by Morgantown Energy Technology Center, Department of Energy, Morgantown, West Virginia (Dec., 1983). Proceedings to appear.

5. Salam, L., "An Experimental Investigation of Fixed-Bed Coal Gasification", M.S. Thesis, Washington University, St. Louis (August, 1983).

Coal Analysis

Mine	Wyodak
Town	Campbell
County	Campbell
State	Wyoming
Abbreviated ID	Wyo 1
Sample Date	7-15-78
Bin #	3500

Proximate Analysis:
As Received

Moisture	31.87
Volatile Matter	32.46
Fixed Carbon	30.16
Ash	5.51
Heating Value (Btu/lb)	7978

Ultimate Analysis:
Moisture-free

Ash	8.09

Moisture- and Ash-free

Hydrogen	5.75
Carbon	74.05
Nitrogen	1.39
Sulfur	0.53
Oxygen (by diff)	18.28
Heating Value MAF (Btu/lb)	12,742
H/C Ratio	0.93

Table 1. Analysis of Coal Used in the Gasification Runs

Char Loaded:	3645.7 gms devolatilized Wyodac char	
Char Composition:	83.56% Carbon	
	11.97% Ash	
	2.33% Oxygen	> Moisture included
	1.02% Hydrogen	> Moisture included
	0.62% Nitrogen	
	0.50% Sulfur	
Time 0-45 min.		
INLET	Air Flowrate:	1.478 m^3/hr*
	Water Flowrate:	3.48 gm/min
	O_2/H_2O:	2.12 gm/gm (1.192 mol/mol)
OUTLET	Product Gas Flowrate:	2.055 m^3/hr*
	Total Condensate:	0 gm
Time 45-580		
INLET	Air Flowrate:	1.206 m^3/hr*
	Water Flowrate:	3.48 gm/min
	O_2/H_2O:	1.73 gm/gm (0.975 mol/mol)
OUTLET	Product Gas Flowrate:	2.022 m^3/hr*
	Total Condensate:	382.2 gms
Unreacted Carbon:	697.8 gms	
Reactor Pressure:	0.1910 MPa	
Original Bed Length:	85.7 cm	
Final Bed Length:	approximately 12.0 cm	

* at 25°C, 0.1013 MPa

Table 2. Summary of Operating Conditions for Gasification Run #072483

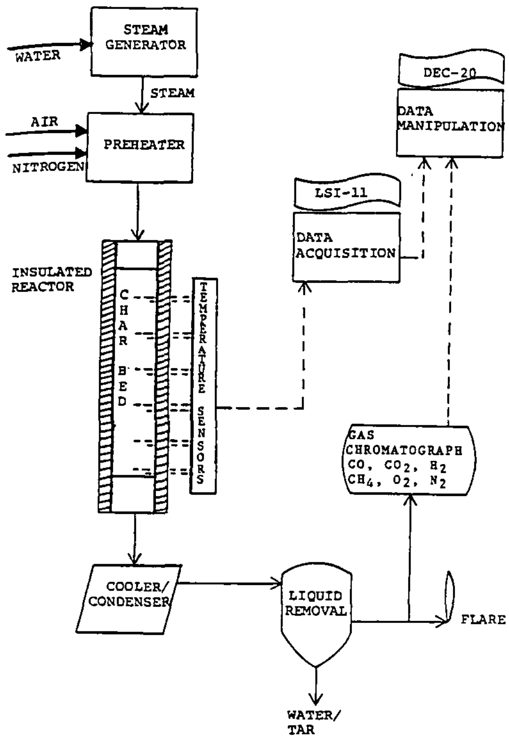

Figure 1. Schematic of Experimental Setup

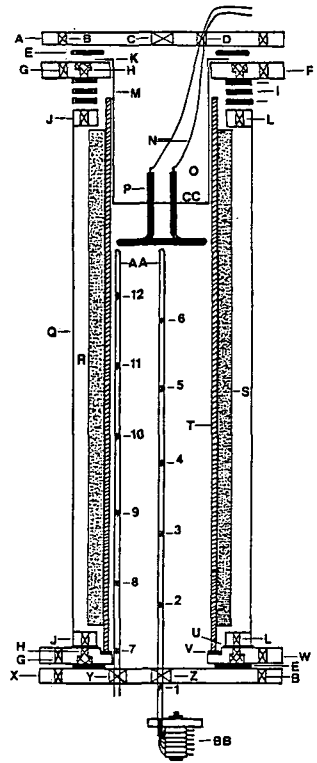

Figure 2. Detail of Gasification Vessel. See next page for Legend.

A - 1 cm thick x 19 cm diameter 304 stainless steel top cover
B - 6 - bolt holes
C - 1/4" FPT for stainless steel inlet fitting (centered)
D - 1/4" FPT for stainless steel ignition lead fitting (2 cm from center)
E - 1/8" (0.3175 cm) compressed asbestos (casp) gasket seals basket flange bolt holes H and cover
F - 19 O.D. x 7.75 cm I.D. steel top flange 1 cm thick
G - 6 - 1/4"-20 threaded bolt holes
H - 6 - recessed bolt holes
I - 3 - 1/8" casp gasket seals and shims top flange
J - 14.9 O.D. x 11.6 cm I.D. steel retaining flanges (1 cm thick) welded inside each end of steel shell
K - 10.8 O.D. x 7.6 cm I.D. stainless steel basket flange (0.0051 cm thick) welded to basket
L - 6 - 1/4"-20 threaded bolt holes
M - 12.7 x 10 cm stainless steel sheet (0.0051 cm thick) rolled and welded to form a 7.6 cm diameter tube for basket wall
N - Asbestos braided copper ignition leads
O - 1/2" (1.27 cm) Diamonite (95% alumina grinding media) ceramic beads
P - 1/4" x 12" (0.635 x 30.4 cm) Incoloy sheathed tubular heater bent to form 5.7 cm loop with 7 cm perpendicular legs
Q - 6" O.D. x 47.7" (15.24 x 121.2 cm) steel pipe for outside wall (0.1651 cm wall)
R - 1" x 24" x 48" (2.54 x 60.96 x 121.92 cm) Kaowool 2600 refractory blanket wraps liner twice
S - Preformed refractory sleeves (Kaowool 2600), split and slid over liner. Refractory cement fills resulting gap
T - 3-3/4" O.D. x 48" (9.525 x 121.92 cm) 304 stainless steel liner (0.3048 cm wall)
U - 1/8" casp gasket seals bottom flange
V - 1/8" casp gasket seals liner bottom
W - Bottom flange same as F with 9.75 cm shoulder 7 mm deep
X - Same as A for bottom cover
Y - 1/8" FPT for stainless steel thermowell fitting
Z - 1/4" FPT for stainless steel exit and thermowell tee fitting

AA - 3/16" O.D. (0.4762 cm) Inconel thermowells 117 and 122 cm
BB - Aluminum thermocouple plug mounting block with set screw
CC - Perforated stainless steel basket bottom (4 x 7/32" holes/inch)

Thermocouple Locations From Top of Well (Bed)

1. 113.0 cm	7. 105.1 cm
2. 91.8 cm	8. 85.7 cm
3. 71.1 cm	9. 65.7 cm
4. 51.1 cm	10. 44.4 cm
5. 29.8 cm	11. 24.3 cm
6. 11.0 cm	12. 4.8 cm

Note all thermocouples are 0.02" (0.0508 cm) diameter Inconel sheathed chromel/alumel rated at 1150°C.

Legend for Figure 2

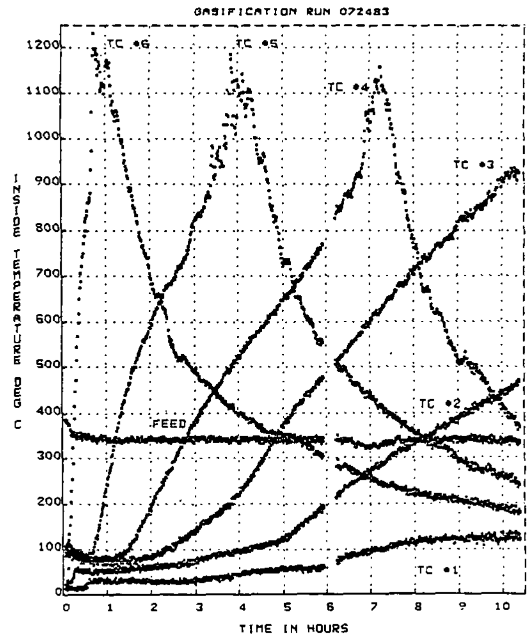

Figure 3. Temperature Profiles in the Gasifier (Central Thermowell)

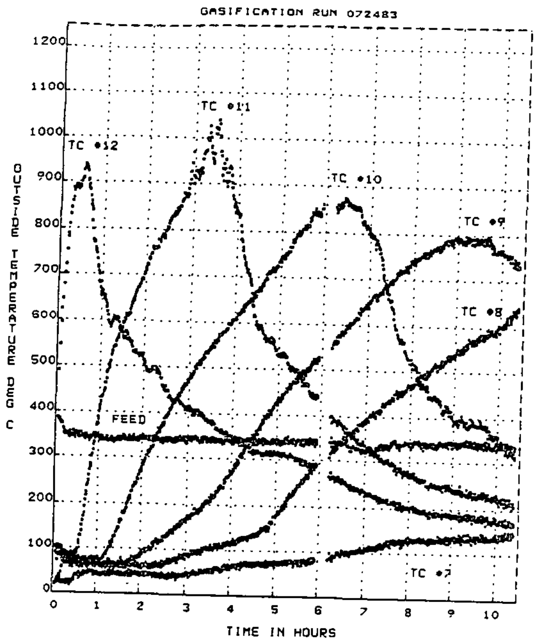

Figure 4. Temperature Profiles in the Gasifier (Thermowell near the Wall)

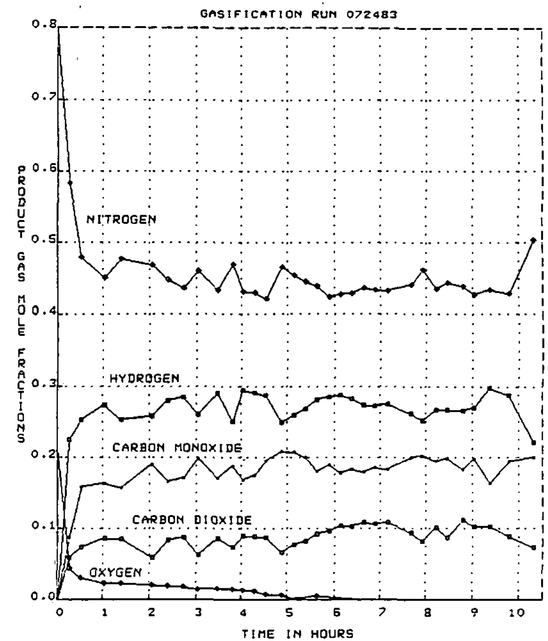

Figure 5. Product Gas Composition as a Function of Time

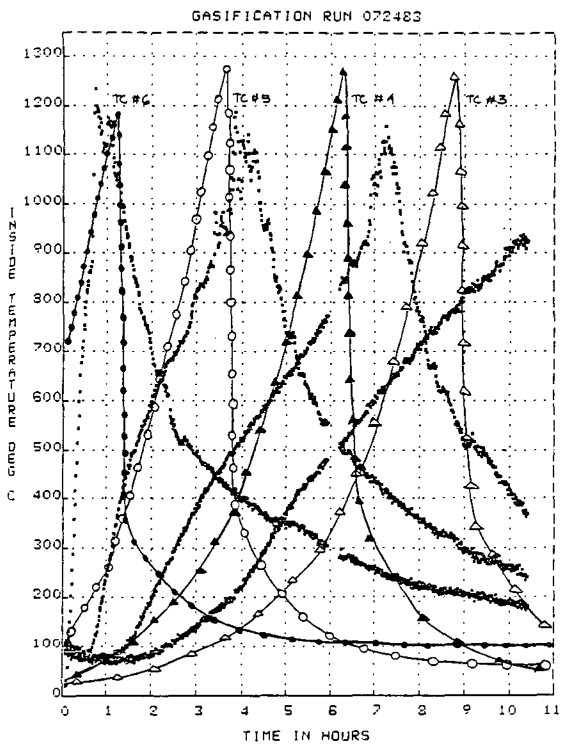

Figure 6. Comparison of Temperature Histories at Thermocouple Locations, Inner Thermowell. Straight Lines are Model Predictions.

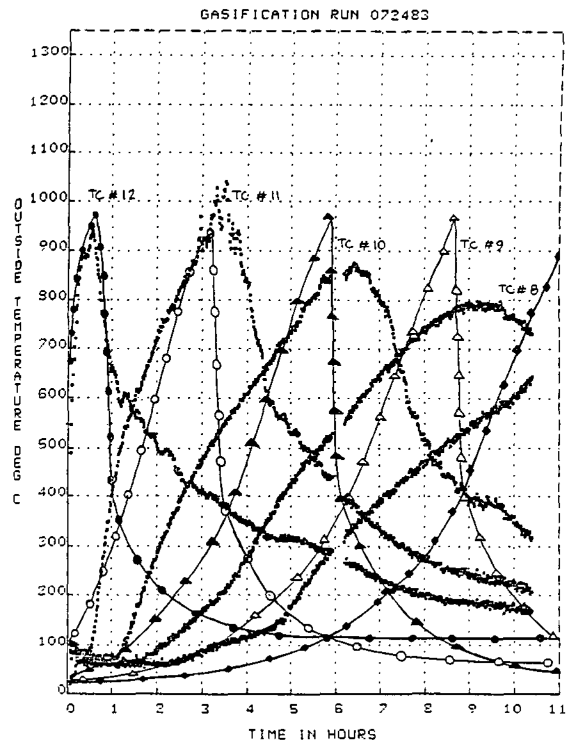

Figure 7. Comparison of Temperature Profiles for the Thermocouples near the Wall. Straight Lines are Model Predictions.